Two-Handed Marking Menus for Multitouch Devices

Kenrick Kin
Björn Hartmann
Maneesh Agrawala

Electrical Engineering and Computer Sciences
University of California at Berkeley

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KENRICK KIN
University of California, Berkeley
Pixar Animation Studios
BJÖRN HARTMANN
University of California, Berkeley
and
MANEESH AGRAWALA
University of California, Berkeley

We investigate multi-stroke marking menus for multitouch devices and we show that using two hands can improve performance. We present two new two-handed multi-stroke marking menu variants in which users either draw strokes with both hands simultaneously or alternate strokes between hands. In a pair of studies we find that using two hands simultaneously is faster than using a single, dominant-handed marking menu by 10-15%. Alternating strokes between hands doubles the number of accessible menu items for the same number of strokes, and is similar in performance to using a one-handed marking menu. We also examine how stroke direction affects performance. When using thumbs on an iPod Touch, drawing strokes upwards and inwards is faster than other directions. For two-handed simultaneous menus, stroke pairs that are bilaterally symmetric or share the same direction are fastest. We conclude with design guidelines and sample applications to aid multitouch application developers interested in using one- and two-handed marking menus.

Categories and Subject Descriptors: H.5.2 [**User Interfaces**]: Interaction styles

Additional Key Words and Phrases: Two-handed multi-stroke marking menus, multitouch

1. INTRODUCTION

Marking menus are gesture-based menus that allow users to select a menu item by drawing a directional stroke [Kurtenbach 1993]. Multi-stroke marking menus extend the basic technique and allow users to efficiently traverse a hierarchy of submenus by drawing a sequence of strokes [Zhao and Balakrishnan 2004]. These techniques are effective because they are simple to perform. Strokes are scale-independent and users can draw them in-place and in an eyes-free manner. Extensive studies have shown that users can draw directional strokes quickly and accurately [Kurtenbach and Buxton 1993; 1994; Moyle and Cockburn 2002; Zhao et al. 2006]. Marking menus also facilitate novice to expert transition. However, marking menu research has primarily focused on studying the use of one-handed marking menus with either mouse or stylus-based input devices.

Multitouch input devices have recently become a popular alternative to both the mouse and stylus, particularly for small-screen personal devices such as the Apple iPhone/iPod Touch [Apple] and for large-screen co-located collaborative work surfaces [MERL ; Microsoft ; PerceptivePixel]. Marking menus are a good

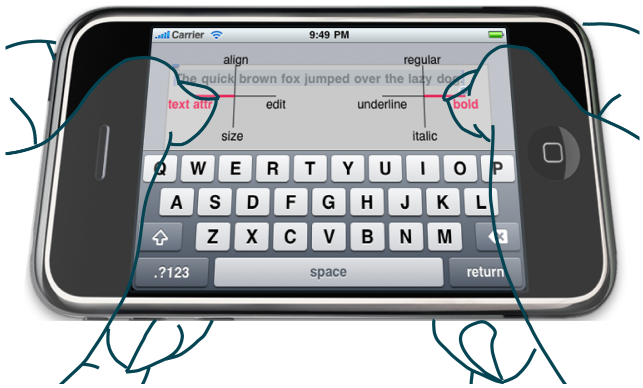

Fig. 1. Using a two-handed ordered marking menu the left thumb strokes to select "Text Attributes" and then the right thumb selects "Bold" to modify the sentence. With a two-handed simultaneous marking menu users draw both strokes at the same time.

match for these devices because they require very little screen-space to perform. Because marking menus are gesture-based techniques, they do not require precise targeting and thereby circumvent the fat finger problem [Potter et al. 1988]. And unlike a mouse or stylus, such multitouch devices detect multiple points of contact and thereby support two-handed interactions. These devices have the potential to significantly increase the efficiency of interaction because users can overlap their hand motions and work with both hands in parallel.

In this paper we examine the speed and accuracy of multi-stroke marking menus with two multitouch devices; a small-screen Apple iPod Touch operated with the thumbs (Figure 1) and a Fingerworks iGesture [Fingerworks] operated with the index or middle fingers as one would on a large-screen surface. Our primary contribution is the design and evaluation of two new two-handed variants of multi-stroke marking menus:

Two-Handed Simultaneous: Users draw two strokes, one with each hand, at the same time. This variant is designed to maximize parallelism in hand motions and thereby offer the fastest selection times.

Two-Handed Ordered: Users alternate the hand used to draw each stroke. Since either hand (left or right) can start the stroke sequence, this variant offers access to twice as many menu items for the same number of strokes, while also allowing for some overlap in hand motions.

We compare the speed and accuracy of these two-handed designs to one-handed marking menus. We find that the two-handed simultaneous technique outperforms the single, dominant-handed technique by 10-15% in total time. However we show through a longitudinal study spanning four hours over five days, that obtaining this performance gain requires some practice. As users gain familiarity with the two-handed design selecting a menu item becomes proceduralized and autonomous, allowing two hands to outperform one hand. While the two-handed ordered approach is not significantly faster than the one-handed approach in total time, it doubles the number of accessible menu items.

The kinematics of the hand impose constraints on the range of motions different fingers can make. It may be easier to draw individual strokes or pairs of strokes in some directions rather than others. To better understand these constraints, we also examine how stroke direction affects speed and accuracy. In the context of one-handed marking menus we find that drawing a stroke using either thumb is fastest when drawing upwards or inwards compared to the other directions. In the context of two-handed simultaneous marking menus, we find that drawing pairs of strokes in which the left and right strokes are either bilaterally symmetric or share the same direction is faster than drawing the other pairs. We conclude with a set of design guidelines that multitouch designers should consider when developing one- or two-handed multi-stroke marking menus at both handheld (iPhone/iPod Touch) and larger (iGesture/iPad) scales. We present several demonstration applications that show how two-handed marking menus could be used to support real-world tasks and to facilitate the transition from novice to expert use.

2. RELATED WORK

Our techniques build on three areas of related work.

Hierarchical Marking Menus: Kurtenbach and Buxton [Kurtenbach 1993; Kurtenbach and Buxton 1993; 1994] introduced marking menus and showed that these menus exhibit a number of desirable properties. Marking menus are *scale-independent* – the selection depends only on the orientation of the stroke, not on its length, and therefore users can efficiently draw short strokes with ballistic motions to select items [McGuffin et al. 2002]. Users can draw strokes *in-place* and do not have to make large round-trip traversals to select items from a fixed location menu. Moreover, users can draw the straight-line strokes in an *eyes-free* manner without diverting attention from their primary task. Finally, marking menus provide a seamless *novice-to-expert transition* path; novices draw exactly the same selection strokes as experts.

However, a drawback of marking menus is that selection accuracy depends on menu *breadth*, or the number of items that appear in the menu. Kurtenbach and Buxton [1993] found that accuracy declines significantly when breadth is greater than eight items. Compound-stroke [Kurtenbach and Buxton 1993] and multi-stroke [Zhao and Balakrishnan 2004] marking menus allow for hierarchical traversal of marking menus using either zig-zag strokes or a sequence of strokes. At breadth-8, however, these techniques perform well only up to depth-2 or depth-3 respectively. More recent techniques have used additional stroke attributes such as stroke position [Zhao et al. 2006] and curvature [Bailly et al. 2008] to further increase menu breadth. All of these techniques have focused on one-handed input. While we adopt the multi-stroke approach, our work focuses on the design of two-handed marking menus that increase either the selection speed or the number of accessible menu items.

Marking Menus on Touch Devices: Touchpads that can track a single point of contact have been commonplace on laptops for the last decade. Balakrishnan and Patel [1998] integrated such a touchpad with a mouse to allow the non-dominant hand to select commands using a compound-stroke marking menu. Isokoski and Käki [2002] found that curved strokes were more accurate but slower in movement time than drawing straight-line selection strokes. Touch-sensing screens are now commonplace on mobile devices. Karlson et al. [2005] used directional strokes for thumb-based navigation on a PDA. Yatani et al. [2008] used a combination of position and directional strokes to disambiguate the selection of closely packed items on a touch-based mobile device. Lepinski et al. [2010] have developed chording marking menus in which users draw simple directional strokes using combinations of fingers on a single hand. While all of these stroke-based techniques are designed for touch-based devices, none of them have examined the use of multiple strokes in different directions or two-handed interactions.

Bimanual Interaction Techniques: The Kinematic Chain Theory of Guiard [1987] details the way hands work together to perform tasks in parallel. Many bimanual interaction techniques assign asymmetric roles to the hands where the non-dominant hand sets the frame of reference and the dominant hand performs fine-scale interactions within this reference frame [Balakrishnan and Hinckley 1999; Buxton and Myers 1986; Hinckley et al. 1997; Kabbash et al. 1994]. Other techniques assign symmetric roles in which both hands perform similar actions [Balakrishnan and Hinckley 2000; Casalta et al. 1999; Latulipe et al. 2005; Latulipe et al. 2006; Owen et al. 2005].

Odell et al. [2004] present an asymmetric bimanual marking menu technique in the context of a shape drawing system. The dominant hand selects a shape and the non-dominant hand selects a command to perform on this shape using a marking menu. Unlike this approach we develop symmetric two-handed marking menus in which both hands perform the same actions. By splitting the strokes of a multi-stroke marking across both hands we allow for overlap in the hand motions and increase the speed of the interaction.

Controllers for console-based gaming systems such as the XBox usually include two joysticks, one for each hand. Wilson and Agrawala [2006] developed a two-joystick based text-entry system using an onscreen keyboard and they have shown that such a symmetric bimanual approach is faster than using the default, single joystick technique. TwoStick [Költringer et al. 2007] extends Quikwriting [Perlin 1998], a technique that uses directional joystick movements to enter text, for use with two joysticks. Weegie [Weegie] is another two-stick-based text entry system in which each stick operates a separate marking menu. Unlike our two-handed marking menus, the two menus in Weegie work independently of one another.

3. DESIGNING TWO-HANDED MARKING MENUS

One-handed multi-stroke marking menus have proven to be effective for use with a stylus or mouse because they are scale-independent, in-place, eyes-free, and provide a seamless novice-to-expert transition. We extend multi-stroke marking menus for use on multitouch devices by splitting the stroke sequence between two hands. We consider several aspects of two-handed operation that can further increase menu selection performance:

Overlapping Motion: Users can overlap motions of their hands and this parallelism can reduce the time required to complete the interaction.

Handedness: Multitouch devices detect multiple points of contact and we can apply simple heuristics based on the relative position of each contact to identify the hand that produced each contact – e.g. the left-most touch is from the left hand and vice versa. We can then increase the number of menu items that are accessible with a single stroke, by assigning a different set of items to each hand. With a hierarchical marking menu of depth-N in which either hand can draw each stroke we can use handedness to provide access to 2^N additional items. However, if the same hand is used to make more than one stroke in sequence the potential for overlapping motion is reduced.

Chunking: Buxton [Buxton 1986] has shown that users can mentally group together frequently co-occurring compound motor tasks into a single chunk that they automatically perform together. With two-handed multitouch devices, users can draw a pair of strokes simultaneously, one with each hand, and may learn to chunk these pairs together into a single action. Thus, users can mentally flatten two levels of a multi-stroke hierarchy into a single level, and convert a breadth-M, depth-2 marking menu into a breadth-M^2, depth-1 menu. Such increased breadth may allow interface designers and users to fit more items in a single cognitive grouping.

Based on these design considerations we propose the following two-handed multi-stroke marking menus designs:

3.1 Two-Handed Simultaneous Marking Menus (2HS)

Users simultaneously draw two strokes, one with each hand. Users can draw additional stroke pairs to traverse a menu hierarchy. This variant is designed to maximize overlap of motions and also facilitates chunking of the stroke pairs into a single mental action. This variant does not consider handedness. Therefore, for a given number of strokes it does not increase the number of accessible menu items over the one-handed multi-stroke marking menu design. However, when users chunk pairs of simultaneous strokes this variant can be considered as squaring the breadth of the menu.

3.2 Two-Handed Ordered Marking Menus (2HO)

Users draw a sequence of strokes with alternating hands. Although the strokes must be drawn in order, the ordering only depends on the start-time (initial contact) of the stroke and users can begin a second stroke before the first stroke is complete to increase motion overlap. This variant considers handedness, but since the hands are forced to alternate, only the hand used to initiate the stroke sequence can vary (left or right). Thus, this approach doubles the number of accessible menu items accessible for a fixed number of strokes. Although using handedness can provide up to 2^N possible sequences, our ordered design that alternates hands considers only a subset of this full space.

4. USER STUDY 1

To investigate the performance benefits of our two-handed multi-stroke marking menu designs we conducted a first user study comparing both of our designs to standard one-handed multi-stroke marking menu designs. To simplify analysis we selected only right-hand dominant participants, but we included both the right- and left-handed unimanual marking menus in our study. We conducted the experiment using two multitouch devices – an iPod Touch to represent handheld interaction and the iGesture to represent larger-screen interaction. Our hypotheses are:

Fig. 2. The Fingerworks iGesture multitouch pad.

H1: Of the one-handed conditions the right-handed multi-stroke marking menu will outperform the left-handed multi-stroke marking menu. Since our participants are right-handed, their dominant hand should move more quickly and accurately than their non-dominant, left hand.

H2: The two-handed simultaneous menu will be faster for selecting menu items than all other menus including two-handed ordered and the one-handed menus. The two-handed simultaneous design maximizes the opportunity to overlap hand motions and should therefore reduce selection time.

H3: The two-handed ordered menu will be faster than a one-handed marking menu for selecting a menu item. Users do not have to wait for one stroke to finish before starting the next stroke and may be able to overlap their hand movements.

Multi-stroke marking menus depend on the ability to draw directional strokes. Yet, hands impose kinematic constraints that make it easier to draw strokes in some directions and more difficult others. Prior work on marking menus has studied the speed and accuracy with which users can draw one or more directional strokes in the context of stylus and mouse-based marking menus [Kurtenbach and Buxton 1993; 1994; Moyle and Cockburn 2002; Zhao et al. 2006; Zhao and Balakrishnan 2004]. Working with two hands using touch-based devices is likely to impose a different set of constraints on the hand motions. Thus, our study also investigates how well users can draw directional strokes with their left and right hands, as well as pairs of such strokes when the pairs are drawn with two hands.

4.1 Participants and Apparatus

We recruited 16 right-handed participants (12 male, 4 female, between 21 and 26 years old). All were experienced computer users and ten were experienced iPhone or iPod Touch users. None of the participants had experience with marking menus or with large multitouch screens. Participants performed the experiment on two multitouch devices:

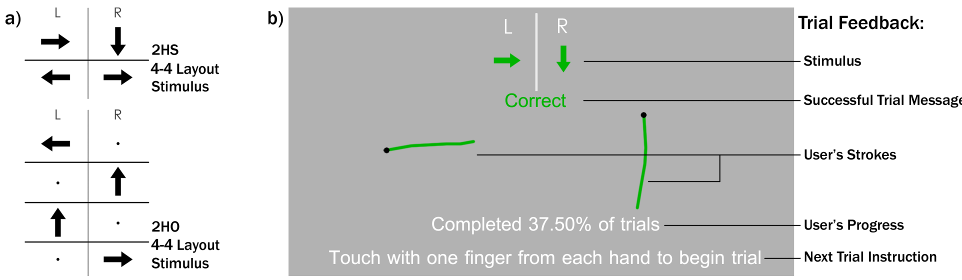

Fig. 3. a) Top: Example stimulus for the two-handed simultaneous technique. Bottom: Example stimulus for the two-handed ordered technique. b) Screenshot of experimental setup with feedback given after a successful trial.

Apple iPod Touch: The iPod Touch is a commonly used handheld multitouch device with a working area of 7.5×5 cm and display resolution of 480×320 pixels. Participants used their thumbs on this device.

Fingerworks iGesture: The iGesture is an indirect multitouch pad with a working area of 16.5×12.4 cm (Figure 2) mapped by absolute coordinates to a 40.6×30.5 cm Dell monitor with a display resolution of 1600×1200 pixels. The study ran on Mac OS X. Participants used either their index fingers or middle fingers on this device.

4.2 Task and Stimuli

We designed the study to test expert-level performance. However, our participants had practically no prior experience using marking menus. Training participants to use multi-stroke marking menus with realistic menu items would force them to learn a complex menu organization. An expert would require little effort to recall the necessary strokes for a command. To better elicit expert-level performance with far less training, we adopted the strategy of previous marking menu studies [Kurtenbach and Buxton 1993; Zhao et al. 2006; Zhao and Balakrishnan 2004] and gave participants stimuli in the form of arrows that directly indicated the strokes they had to make.

Examples of the stimuli we used are shown in Figure 3a. Arrows appear in separate columns to indicate the hand that should draw the stroke. Pairs of arrows in the same row indicate strokes that must be drawn simultaneously. Participants had to draw the strokes in order from top to bottom and in the one-handed conditions (not shown in Figure), the stimulus only contained arrows in either the left or right column.

To begin a trial the participant tapped the screen with one finger for the one-handed conditions or one finger on each hand for the two-handed conditions. The stimulus appeared at the top of the screen and, following the approach of Zhao et al. [Zhao et al. 2006], as soon as the participant touched the input device the cue disappeared so that the subject could not read the arrows in between drawing marks. This approach is designed to better elicit expert-level performance because it prevents subjects from interleaving drawing the strokes and reading the stimulus. We asked the participant to select the item menu as quickly and accurately as possible.

After the participant made the designated number of strokes (2 or 4), a feedback screen showed whether or not the trial was successful and the percentage of trials completed so far (Figure 3b). On correct trials we colored the strokes and stimuli green, and on incorrect trials we colored them red. The participant could rest between trials while the feedback was onscreen and they could continue to the next trial by tapping.

4.3 Study Design

Our experiment is a within subjects design that considers the effects of three independent variables: the *device*, *menu technique* and *menu layout*. We fully counterbalanced the device variable so that half the participants used the iPod Touch first and the other half used the iGesture first.

Participants had to select menu items using one of four menu techniques; left-handed multi-stroke marking menu (1HL), right-handed multi-stroke marking menu (1HR), two-handed simultaneous marking menu (2HS), or two-handed ordered multi-stroke (2HO). We used a Latin square to counterbalance the ordering of the menu techniques.

For each menu technique we tested three different breadth-depth menu layouts: 4-2, 8-2, and 4-4 (first number denotes breadth, second denotes depth). We only considered the number of strokes in multiples of two, so that strokes could be evenly distributed between hands for the two-handed conditions. Although the two-handed techniques would work with an odd number of strokes we believe it should be possible to extrapolate performance on those conditions from the data for even numbers of strokes.

We fixed the ordering of the three layouts from least complex to most complex (4-2, 8-2, 4-4). As the number of accessible menu items or stroke combinations increases, more trials are necessary to obtain good coverage. Our three layouts include 16, 64 and 256 possible stroke combination and we used 24, 32 and 32 trials respectively. For the 4-2 layout, each stroke combination was performed at least once, in randomized order. For the 8-2 layout there are four possible pairs of on- and off-axis strokes: on-on, on-off, off-on, off-off. We randomized the stroke combinations such that each participant performed 8 trials from each axis grouping. For the 4-4 layout, we randomly chose the stroke combination from amongst all possible combinations for that layout. For the two-handed ordered condition, we randomized the order of the starting hand with half the trials beginning with the left hand.

A trial was considered a miss if any one of the strokes was drawn in an incorrect direction. To check for misses, we compared the angle of the line segment connecting the start and end points of the drawn stroke with the angle of each possible stroke direction in the menu. If the angle of the drawn stroke was closest the angle cued in the stimulus it was considered correct, otherwise it was considered a miss. We added each missed trial to the end of the trial queue so that users would have to perform it again until successful.

Before testing each menu layout we gave participants a practice block to train them in reading the stimulus and move them towards expert-level performance. For the 4-2 conditions we required 20 practice trials, while we required 8 practice trials

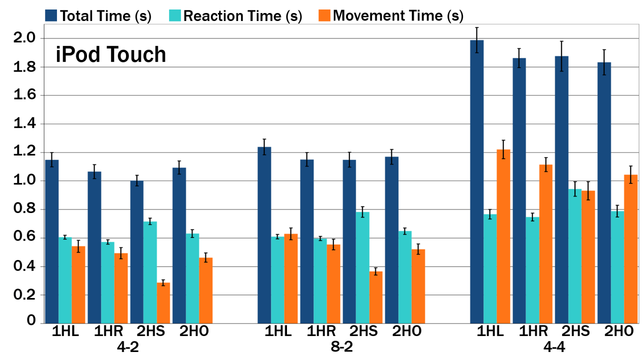

Fig. 4. Average times (with std. error) for each menu technique and menu layout on the iPod Touch.

for the 8-2 and 4-4 conditions. In all cases participants had the option to continue practicing until they felt comfortable with the task. The entire experiment took each participant roughly one hour.

We measured four dependent variables: *reaction time*, *movement time*, *total time*, and *accuracy*. Reaction time was the interval between the first display of the stimulus and the start of the touch beginning the first stroke. It represents the time required for participants to process the stimulus and decide which strokes to draw. Movement time was the interval between the first touch and completion of all strokes and represents the time required to physically draw the strokes. Total time was computed as the sum of the reaction and movement times. We only considered timing data from correct trials to better account for expert-level performance. We computed accuracy as the fraction of correctly performed trials to the total number of uncorrected trials. We did not include the trials that were added to the end of the queue as the result of a miss in our accuracy measure.

5. RESULTS: IPOD TOUCH

Average times and accuracies for all of the iPod Touch conditions are shown in Figures 4 and 5. Since each menu layout offers a different total number of accessible menu items we focus on comparing performance of the menu techniques within each menu layout rather than across layouts. For each menu layout and each dependent variable we computed a separate repeated measures ANOVA using menu technique as the only factor. For each of the menu layouts we also compared performance across different combinations of stroke pairs. Finally, for the two-handed conditions we examined differences in motion overlap and the effects of the starting hand on the ordered technique.

The overall trends in timing and accuracy were similar across the three menu layouts. For brevity we present the complete numerical results for only the 4-2 layout and then summarize the main differences for the 8-2 and 4-4 layouts. (Complete numerical results are in the electronic appendix.)

5.1 4-2 Menu Layout

Total Time: The average total times were 1149 ms for 1HL, 1065 ms for 1HR,

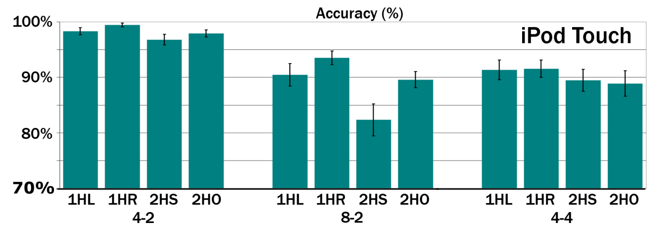

Fig. 5. Average accuracies (with std. error) for each menu technique and menu layout on the iPod Touch.

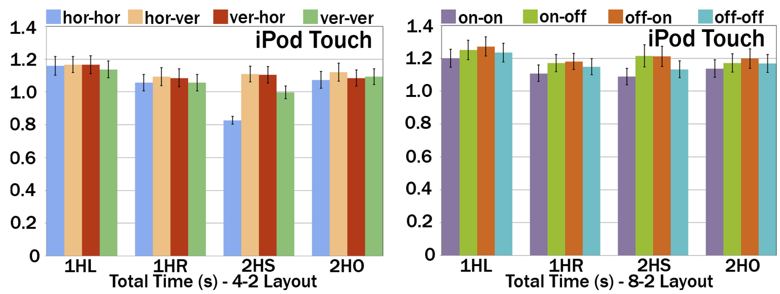

Fig. 6. Left: Average total times for horizontal or vertical stroke combinations for the 4-2 layout. Right: Average total times for on- or off-axis stroke combinations for the 8-2 layout. Both graphs are for the iPod Touch. Standard error bars are shown.

1003 ms for 2HS, and 1094 ms for 2HO. Menu technique had a significant effect on total time ($F_{3,45}$= 6.09, p=0.001). Pairwise t-tests show that average total times differed significantly for all pairs ($p<0.007$), except for the pairs 1HL-2HO (p=0.133), 1HR-2HS (p=0.142), and 1HR-2HO (p=0.439). In general total time was similar across the four conditions with increased reaction time making up for decreased movement time in the two-handed conditions.

Reaction Time: The average reaction times were 606 ms for 1HL, 572 ms for 1HR, 716 ms for 2HS, and 631 ms for 2HO. Menu technique had a significant effect on reaction time ($F_{3,45}$=19.19, $p<0.001$). Pairwise t-tests show that average reaction times differed significantly for all pairs ($p<0.03$), except for 1HL-2HO (p=0.277). Reaction time was slowest for two-handed simultaneous.

Movement Time: The average movement times were 542 ms for 1HL, 493 ms for 1HR, 287 ms for 2HS, and 463 ms for 2HO. Menu technique had a significant effect on movement time ($F_{3,45}$=24.20, $p<0.001$). Pairwise t-tests show that average movement times differed significantly for all pairs ($p<0.03$), except for the pair 1HR-2HO (p=0.285). Movement for two-handed simultaneous was the fastest, movement for the right-handed multi-stroke and two-handed ordered were next fastest, and movement for the left-handed multi-stroke was the slowest.

Accuracy: The average accuracies were 98.3% for 1HL, 99.5% for 1HR, 96.8% for 2HS, and 97.9% for 2HO. There was no significant difference in accuracy ($F_{3,45}$=2.29, p=0.091) due to menu technique.

Horizontal and Vertical Strokes: For the 4-2 layout, we compared horizontal-horizontal, horizontal-vertical, vertical-horizontal, and vertical-vertical selections

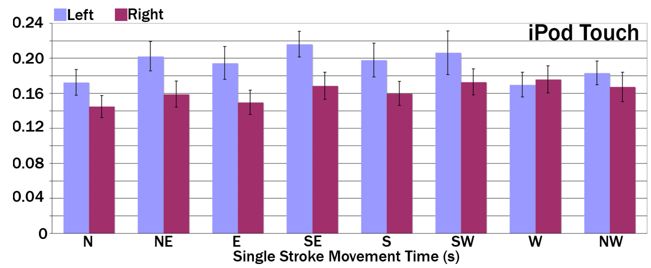

Fig. 7. First stroke average movement (with std. error) times using the iPod Touch for the 8-2 layout.

for each menu technique. The average total times were usually longer for strokes along different axes as shown in Figure 6 (Left). Menu technique and the stroke combinations both had a significant effect on total time ($p<0.001$). There was also a significant interaction ($F_{9,135}=20.99$, $p<0.001$); the 2HS technique has a very strong separation in performance in same-axis pairs compared to different-axis pairs, while the other techniques do not. There was no significant difference in accuracy.

Two-Handed Motion Overlap and Starting Hand: To assess the level of motion overlap in the two-handed conditions we computed the delay between the initial touch of the first hand and the initial touch with the second hand. A shorter delay indicates a greater likelihood of overlap between the hand motions. The average delay for 2HS was 35 ms, compared to 254 ms for 2HO ($p<0.001$). For 2HO we found no significant differences in time or accuracy between trials started with the left hand and those started with the right hand.

5.2 8-2 Menu Layout

Time, Accuracy and Motion Overlap: Figure 4 shows that trends in total, reaction and movement times were similar for the 8-2 and 4-2 layouts. However, as shown in Figure 5, average accuracy declined in the breadth-8 layout to 90.4% for 1HL, 93.5% for 1HR, 82.3% for 2HS, and 89.6% for 2HO compared to the breadth-4 layout. Menu technique had a significant effect on accuracy ($F_{3,45}=6.41$, $p=0.001$). Pairwise t-tests show that average accuracies differed significantly for all pairs ($p<0.05$), except 1HL-1HR ($p=0.163$) and 1HL-2HO ($p=0.695$). The average delay between touches for 2HS was 52 ms, compared to 298 ms for 2HO ($p<0.001$), indicating more motion parallelism in the simultaneous condition. Again for 2HO we found no significant difference in speed or accuracy due to the starting hand.

On- and Off-Axis Strokes: We compared on-on, on-off, off-on, and off-off axis selections for the 8-2 layout. Total times are shown in Figure 6 (Right). Menu technique ($p<0.01$) and the stroke combinations ($p<0.001$) both had a significant effect on total time. There was also a significant interaction effect ($F_{9,135}=2.38$, $p=0.02$), combinations in which both strokes were either on axis or off-axis performed best. There was no significant difference in accuracy.

Single Stroke Directions: To better understand which individual stroke directions are easiest to perform with the thumbs, we examined the movement time of the first stroke in the 8-2 layout for both of the one-handed conditions as shown in Figure 7. Pooling the data across all directions we found that the right hand

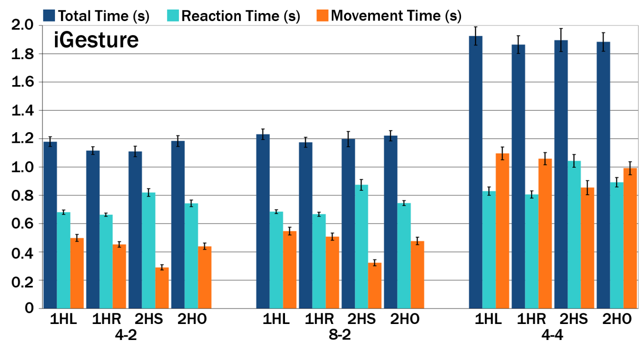

Fig. 8. Average times (with std. error) for each menu technique and menu layout on the iGesture.

(161 ms) was significantly faster than the left hand (191 ms) ($p=0.005$). For each hand we ran separate ANOVA's with stroke direction as the factor and found a significant effect on movement time for both the left hand ($F_{7,105}=3.74$, $p=0.001$) and the right hand ($F_{7,98}=3.46$, $p=0.002$). We removed the data of one participant from the right hand analysis, because one of the stroke directions did not appear as the first stroke in any of the trials for that participant. Examining the average movement times, we found that the left thumb was faster at selecting strokes in the upper left quadrant (N, NW, W directions) and the right thumb was faster at selecting strokes in the upper right quadrant (N, NE, E directions). In addition, on-axis stroke directions tended to be faster than their neighboring off-axis directions.

5.3 4-4 Menu Layout

Time, Accuracy and Motion Overlap: The 4-4 menu layout doubles the number of strokes over the 4-2 and 8-2 layouts and while the total, reaction and movement times also increased (Figure 4), total time did not quite double. The timing trends followed those we saw for the 4-2 and 8-2 layouts. The total time for the two-handed techniques was not significantly faster than for the single dominant-handed condition. While the 2HS technique significantly lowered movement time compared to the other methods, it also increased reaction time and therefore the reduction in total time was not significant. Accuracy for the 4-4 layout was consistent at about 90% across the four menu techniques and as shown in Figure 5, generally fell between the accuracies for the 8-2 and 4-2 layouts. Motion overlap followed the same trends as for the 4-2 and 8-2 layouts.

6. RESULTS: IGESTURE

Average times and accuracies for the iGesture are shown in Figures 8 and 9. Figures 10 and 11 show the average movement times for pairs of stroke directions and single stroke directions in the 8-2 layout condition. Overall the data we obtained using the iGesture device exhibit very similar trends to the iPod Touch data. Again, for brevity we summarize the main similarities and differences between the iGesture and iPod Touch results. (Complete numerical results are in the electronic appendix.)

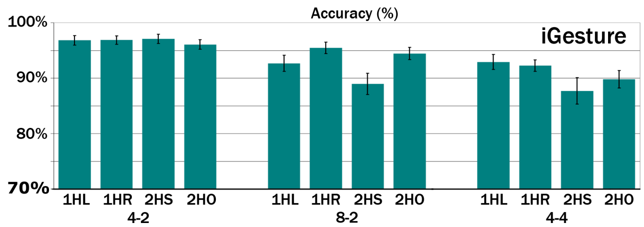

Fig. 9. Average accuracies (with std. error) for each menu technique and menu layout on the iGesture.

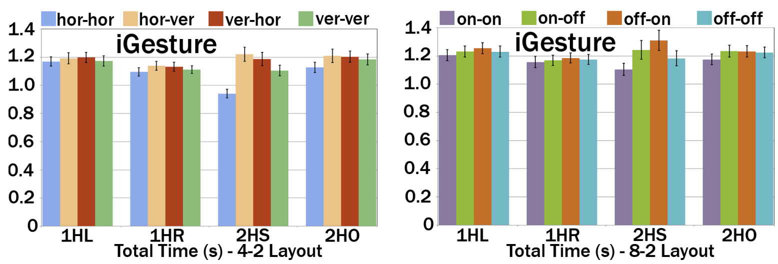

Fig. 10. Left: Average movement times for vertical or horizontal stroke combinations for the 4-2 layout. Right: Average movement times for on- or off-axis stroke combinations for the 8-2 layout. Both graphs are for the iGesture. Standard error bars are shown.

Timing and Accuracy: The iGesture produced similar timing and accuracy trends to the iPod Touch. For each menu layout the two-handed simultaneous technique was significantly faster in movement time but slower in reaction time compared to the other designs. Although the average total time of the left single-handed marking menu was slower than the right handed marking menu, this difference was significant only for the 4-2 layout. Although the two-handed simultaneous design had lower accuracy than the other designs, the accuracy for all menu techniques was greater than 87.7% regardless of layout.

Single Stroke Directions: One difference between the iGesture and iPod Touch results was that all single stroke directions for the 8-2 layout took about the same movement time. Unlike the iPod Touch where the strokes in the upper right or upper left quadrants were fastest for the right and left thumbs respectively, we found no such difference for the iGesture.

7. DISCUSSION

The overall goal of our study was to investigate the performance of multi-stroke marking menus in the context of multitouch devices. We summarize the results as follows:

Dominant-handed multi-stroke marking menus are faster than non-dominant-handed menus. Our results show for one-handed marking menus, the right hand outperforms the left hand for the iPod Touch condition, confirming hypothesis *H1*. Although the average total time of the dominant-handed menu was always faster for the iGesture, it was only significant for the 4-2 layout. In addition, we found no significant difference in accuracy between the right and left

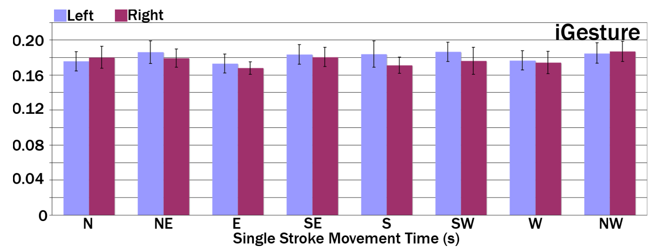

Fig. 11. First stroke average movement times (with std. error) using the iGesture for the 8-2 layout.

hand menus. All of our subjects were right-handed, so it is not surprising that the dominant hand performed better than the non-dominant hand.

Two-handed simultaneous menus are as fast as dominant-handed multi-stroke menus. We hypothesized (*H2*) that the two-handed simultaneous marking menu would outperform the other menu techniques because it maximizes overlap in hand motion. However, the total time was very similar to the dominant-handed technique. Although 2HS was fastest in movement time, 16.5-41.8% faster on the iPod Touch and 19.4-36.4% faster on the iGesture than 1HR, it also incurred a slower reaction time, indicating that users spent more time remembering and planning their strokes. These results do not allow us to accept hypothesis *H2*. However, based on our own experience with 2HS we believe that with practice users can cognitively chunk the simultaneous two-stroke gestures and greatly reduce their reaction time. The two strokes proceduralize into a single automated action, like a form of "muscle memory". As described in the next section, we conducted a longitudinal study to test this hypothesis.

At breadth-4, two-handed simultaneous is just as accurate as the other menu designs, but at breadth-8 it is less accurate. Nevertheless accuracy remained above 82% across all conditions we tested and can improve significantly with practice as we will show in the next section. These results suggests that drawing two strokes simultaneously is a fast technique for selecting menu items and especially accurate for breadth-4 designs.

Two-handed ordered menus are as fast as dominant-handed multi-stroke menus and provide access to twice as many items. Although we hypothesized (*H3*) that the two-handed ordered marking menu would be faster than the one-handed designs due to overlap in hand movement, we found that in most cases total time was not significantly different between the two-handed ordered design and using the dominant hand alone. The reaction times were faster for two-handed ordered than for two-handed simultaneous menus, but slightly slower than for the one-handed menus. This result indicates that planning finger movements takes more time for the two-handed menus. Since starting with the right hand or left hand makes no significant difference on movement time or accuracy, both alternating orders are equally useful for selecting menu items.

Stroke direction affects performance on the iPod Touch. When drawing a single stroke on the iPod Touch, we found a significant difference between hands on the iPod Touch, with the dominant hand faster than the non-dominant hand.

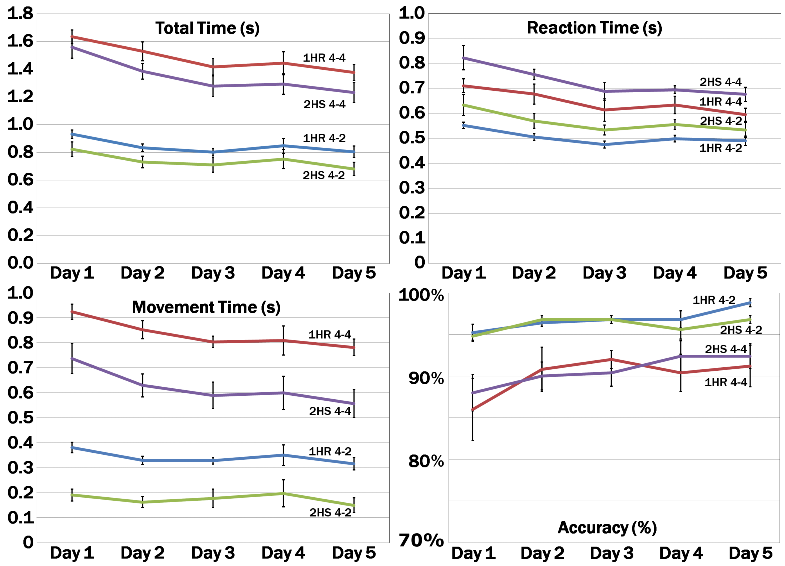

Fig. 12. Average time and accuracy (with std. error) for menu techniques 1HR and 2HS and menu layouts 4-2 and 4-4, across five days.

We also found that stroke direction had a significant effect on movement time. For each hand, participants were fastest at pulling their thumbs up or inward, and on-axis strokes were faster than the neighboring off-axis strokes. On the iGesture, however, we did not find any significant difference between hands nor any significant difference due to stroke direction.

Some stroke pairs are faster to draw than others. We also examined how different combinations of stroke directions affect drawing speed. For the 4-2 layout, pairs of both vertical strokes and both horizontal strokes tended to have faster average total times than the mixed pairs. In the two-handed simultaneous condition, drawing bilaterally symmetric strokes or strokes in the same direction was faster than drawing non-mirrored strokes. For the 8-2 layout, on-on and off-off pairs were faster than the mixed pairs for the two-handed simultaneous design. On-on strokes were slightly faster than off-off strokes on the iPod Touch.

Differences in delay between start of strokes may distinguish simultaneous from ordered design. For the two-handed conditions, the delay between the start of the the first stroke and the second stroke is significantly different between the simultaneous and ordered conditions by about 200 ms. This delay could be used to distinguish which of these two menu techniques the user is performing.

Hand identity and delay can distinguish menu technique. It may be possible to combine all four menu selection techniques in a single application. Assuming users must make at least two strokes to select an item, the system could determine whether the user is invoking a one-handed menu by checking if all strokes were drawn by either the left or right hand. If two hands are used, the system can use the delay between the start of the first and second stroke to determine between the simultaneous or ordered design.

8. USER STUDY 2: LONGITUDINAL EVALUATION

In our first study, we found that the significant improvement in movement time for the two-handed simultaneous technique was offset by an increase in reaction time required to process the stimulus and plan the hand movements. However, with enough practice, users may require less time to plan movements as drawing two strokes at the same time becomes more autonomous. We hypothesize that with practice:

H4: Reaction times for 1HR and 2HS will converge.

H5: The 2HS technique will outperform 1HR in total time.

To test these hypotheses, we conducted a longitudinal study with five right-handed participants. Each participant was given an iPod Touch for use over five consecutive days. Each day the participant spent approximately 45 minutes to perform three blocks of 50 trials for each of the layouts 4-2 and 4-4, using the 1HR and 2HS menu techniques. Participants received no practice trials and our analysis includes all data.

8.1 Longitudinal Results

As shown in Figure 12, the total, reaction and movement times all decrease with practice while accuracy increases. Across both menu layouts 4-2 and 4-4, by day five, 2HS was 10-15% faster in total time and 29-52% faster in movement time than 1HR. However, reaction time remained 10-12% slower for 2HS than for 1HR, even after five days. Finally, on day five, accuracy was between 92.4-96.8% for 2HS and between 91.2-98.8% for 1HR.

For each layout (4-2, 4-4) and dependent variable (total time, movement time, reaction time, accuracy) we ran separate two-way ANOVAs with day and menu technique (1HR, 2HS) as factors. We found significant main effects ($p<0.05$) in all but the following cases; 1) for menu layout 4-2, day did not significantly affect movement time and menu technique did not significantly affect accuracy, 2) for menu layout 4-4, neither day nor menu technique significantly affected accuracy. We found no significant interactions in any of the ANOVAs.

8.2 Longitudinal Discussion

Time and Accuracy: While we cannot accept our hypothesis (*H4*) that reaction times would converge we found that the difference in reaction times between 1HR and 2HS did decrease significantly after five days. The decrease was 29.6% for the 4-2 menu layout and 26.2% for the 4-4 layout, suggesting that time required to coordinate two hand movements diminishes with practice. For the 4-2 layout there was no significant difference in movement time across days. For the 4-4 layout reaction and movement time improved for both techniques, but the movement time advantage for 2HS outweighed the reaction time advantage for 1HR. By day five, total time was faster for 2HS than 1HR by 15.3% for layout 4-2 and 10.3% for layout 4-4, confirming hypothesis (*H5*). In our initial study our two-handed technique had a relatively low accuracy rate for the 4-4 layout (89.5%). Although we did not find the day to have a significant effect on accuracy, the average accuracy did improve from 88.0% to 92.4% after five days. Together these results suggest that although our 2HS technique may be more difficult than the single hand 1HR technique at

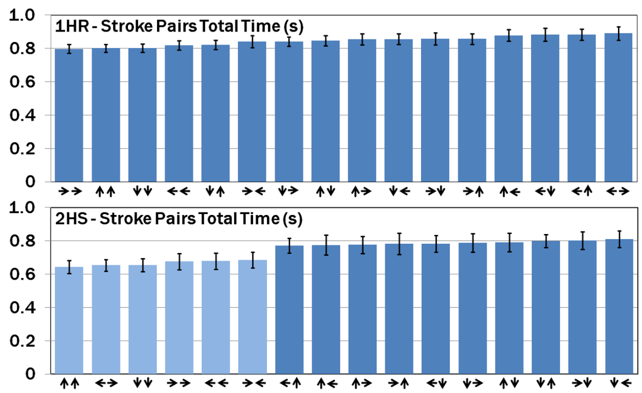

Fig. 13. Average total time (with std. error) per stroke pair for the 4-2 layout. For 2HS, the six fastest times belong to pairs of strokes that are bilaterally symmetric or share the same direction.

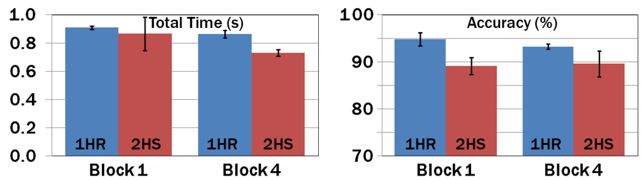

Fig. 14. Average total time and accuracy (with std. error) for the first and last blocks for the 8-2 layout.

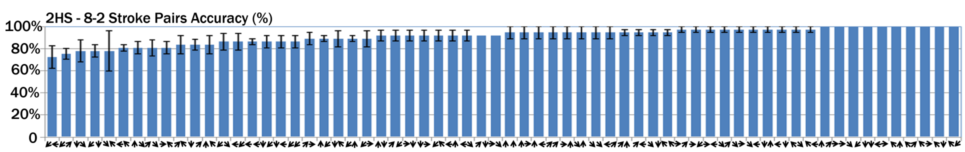

Fig. 15. Average accuracy for all stroke pairs in the 8-2 layout using the 2HS technique. Note that standard error bars are zero when all three participants had the same accuracy.

first, with moderate practice an expert user can access menus items more quickly using 2HS than 1HR.

Stroke Directions: Figure 13 shows the total time in sorted order for each of the 16 stroke pairs in the 1HR condition (top) and the 2HS condition (bottom). For 2HS there is a large jump as the total time to perform a pair of strokes that are bilaterally symmetric or in the same direction is faster than other stroke pairs by over 10%. There is no such jump for 1HR, but the pairs in which both strokes are drawn in the same direction are the four fastest.

8.3 Longitudinal Study: 8-2 Menu Layout

Based on the results of our longitudinal study on the breadth-4 menus we conducted a small follow up experiment with three participants to examine long term performance for the breadth-8 layout using menu techniques 2HS and 1HR. Each

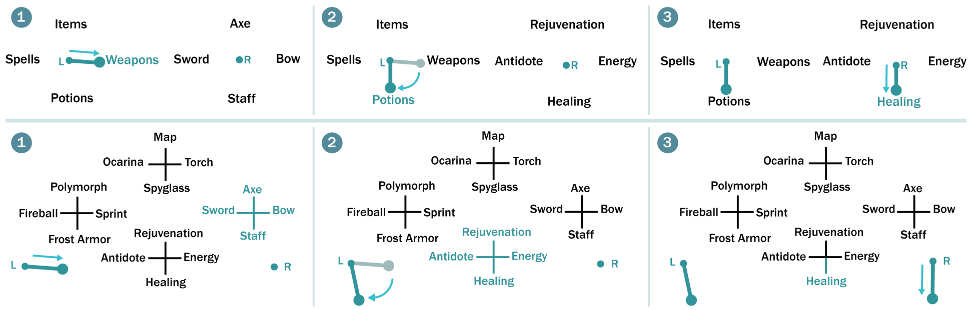

Fig. 16. Top: Hierarchical Display - The left hand explores the parent menu items by dragging through menu items, and the child menu items continuously update for the right hand. Bottom: Full-Breadth Display - The entire menu space is displayed, and the left hand chooses the four-item cluster, while the right hand chooses the item within a cluster.

participants performed four blocks of trials, where each block consisted of three repetitions of the 64 stroke pairs in randomized order. As shown in Figure 14, by the fourth block the total time was 15.4% faster with 2HS than with 1HR and average accuracies were 89.6% for 2HS and 93.2% for 1HR. The speedup is in line with our breadth-4 results. Moreover, the 2HS accuracy of 89.6% is much higher than the 82.3% we saw in our initial study of the 8-2 layout, suggesting that practice can improve accuracy. Although 2HS is not quite as accurate as 1HR, examining the individual stroke pairs for 2HS (Figure 15), we find that when the left stroke is parallel to the SW-NE axis or the right stroke is parallel to the SE-NW axis accuracy drop to 86.6%, while the remaining 36 stroke pairs maintain an accuracy at 95.0%. Our results confirm Karlson et al.'s [2005] observation that for the right thumb, SE-NW strokes are the most difficult to draw. Just as for the breadth-4 layout, we find that pairs of bilaterally symmetric or same-direction strokes (731 ms) are faster to draw than other pairs (815 ms).

9. DESIGN GUIDELINES

Based on our results we make the following design recommendations. Two-handed simultaneous multi-stroke marking menus provide the fastest performance with good accuracy at breadth-4 and acceptable accuracy at breadth-8. The most frequently used commands should be bound to pairs of bilaterally symmetric strokes or same-direction strokes as they are the fastest to perform. For handheld thumb-operated devices it may be possible to improve breadth-8 accuracy by avoiding the use of the SW-NE directions for the left thumb and the SE-NW directions for the right thumb. Alternatively, designers may bind commands that require conscious commitment, such as deletion or quitting, to these pairs that are harder to perform.

With a one-handed marking menu operated by a thumb, the right thumb is faster than the left thumb. Within the right-handed menu the most frequently used menu items should be placed in the upper right quadrant of directions, and within the left-handed menu, the most frequently used menu items should be placed in the upper left quadrant, as those directions had the fastest movement times.

10. DISPLAYING MENU ITEMS FOR NOVICE USERS

Although our studies focused on expert performance, real-world usage of our two-handed designs requires methods for training novice users in the mapping between stroke pairs and menu items. We offer two novice-mode visualizations that facilitate exploration of the menu items bound to stroke pairs.

In a hierarchical display (Figure 16 Top), the left hand selects the parent menu item by dialing through the items [Zhao et al. 2007]. The right menu continuously updates to show the corresponding child menu items. The closest parent and child menu items are always highlighted to indicate which option the user has currently chosen. Users can continuously explore all possible menu items without backtracking or lifting up any fingers. However, navigating a four-stroke menu would still require backtracking if the wrong initial pair was selected.

In a full-breadth display (Figure 16 Bottom), all the items are presented [Zhao et al. 2006], and the left hand specifies the menu cluster, while the right hand specifies the item within a cluster. The cluster that the left hand is currently selecting is highlighted as feedback to the user. The user can dynamically switch to any of the options without lifting up any fingers. This display can be particularly useful when there is no logical way to group items into equally-sized clusters.

11. APPLICATIONS

We have shown that our two-handed multi-stroke marking menus are viable menu selection techniques. Although many iPhone/iPod Touch applications and games use two-thumb controls we have not yet seen two-thumb marking menus on these devices. We believe many such handheld applications could benefit from our two-thumb marking menus and we present several usage scenarios.

Dual-Joystick Navigation: Many iPhone games require players to hold the device in landscape mode and use two virtual joysticks operated by the thumbs, one to control movement and the other to control character orientation. Our two-thumb techniques could be integrated into such games and used to trigger commands such as diffusing or disposing of mines in a mine disposal game (Figure 17). Because our techniques are eyes-free, expert users can keep their focus on the current task and select commands without visually searching for soft buttons to select a command. Examining data from this application we find that users can switch from movement to two-handed menu selection and back in less than 0.5 seconds.

Text Editing: In text-editing mode on touchscreen devices such as the iPhone, the keyboard takes up half the screen, leaving little room for text formatting options. We have integrated our two-handed marking menus into a text-editing application allowing users to quickly change the attributes of the text (Figure 1) by selecting from a two-handed marking menu rather than through soft buttons.

Falling Blocks Game for Training Novice Users: Touch-typing is a complex task that requires coordination of ten fingers. Novice typists often use typing games to become proficient. Similarly, we offer a *Falling Blocks* game to train novices to quickly draw two directional strokes simultaneously to execute commonly used system commands. In the game, colored blocks continually fall down the screen, and each block is associated with a command and a stroke pair. Users must execute the correct strokes to destroy each block before it falls to the bottom

Fig. 17. In this mine disposal game, the user moves a robot using two joysticks. The left joystick controls movement and the right joystick controls orientation. Two-handed marking menus invoke commands as shown in the four screenshots and can be executed anywhere on the screen.

of the screen. In novice mode, the strokes are shown to the user, but in expert mode, the user must remember the mapping between commands and strokes (Figure 18).

The iPhone App Store provides an opportunity for researchers to introduce applications to the general public. As an experiment, we released *Block Blender*, a variant of our *Falling Blocks* application, on the App Store. In the game, blocks continuously fall down the screen and the player must draw the specified pair of strokes to destroy the block. If the blocks stack too high, the game is over. We have had nearly 1000 downloads. Players connected to the Internet will have data about their scores sent back to us. Of the scores we have received, two players destroyed at least 1000 blocks destroyed with 93.7% and 85.1% accuracy. Six players have been able to outscore the author's best score of 184, each doing so in six tries or less. These players were able to stay alive with a new block generated every 0.82 seconds while performing pairs of strokes with average movement times between 0.13 second and 0.29 seconds. Although this application demonstrates that some players can quickly pick up the skill to draw pairs of strokes simultaneously and outperform even the first author, most players did not produce high scores. These players are likely to still be learning the mechanics of the game.

12. CONCLUSION

Two-handed multi-stroke marking menus are effective menu selection techniques for multitouch devices. Our studies of expert-level performance show that the simultaneous variant is faster than one-handed designs and the two-handed variant

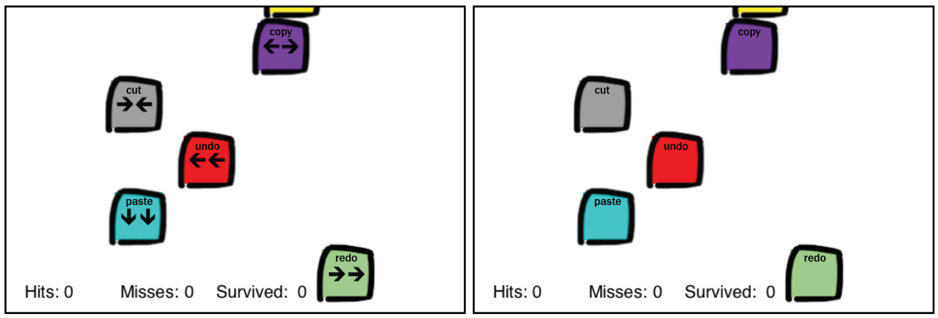

Fig. 18. In the Falling Blocks game, the user must destroy each block by drawing the corresponding strokes. Left: Novice Mode - Strokes are shown to the user. Right: Expert Mode - No strokes are shown.

doubles the number of accessible menu items. Multitouch devices from handheld devices to large-scale tables and walls are rapidly becoming mainstream technologies. We believe that techniques like two-handed marking menus are a step towards exploiting the full potential of these devices.

ACKNOWLEDGMENT

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REFERENCES

Apple. Apple iphone. http://www.apple.com/iphone/.

Bailly, G., Lecolinet, E., and Nigay, L. 2008. Flower menus: a new type of marking menu with large menu breadth, within groups and efficient expert mode memorization. In *Proc. AVI*. 15–22.

Balakrishnan, R. and Hinckley, K. 1999. The role of kinesthetic reference frames in two-handed input performance. In *Proc. UIST*. 171–178.

Balakrishnan, R. and Hinckley, K. 2000. Symmetric bimanual interaction. In *Proc. CHI*. 33–40.

Balakrishnan, R. and Patel, P. 1998. The padmouse: Facilitating selection and spatial positioning for the non-dominant hand. In *Proc. CHI*. 9–16.

Buxton, W. 1986. Chunking and phrasing and the design of human-computer dialogues. In *Proc. IFIP World Computer Congress*. 475–480.

Buxton, W. and Myers, B. 1986. A study in two-handed input. In *Proc. CHI*. 321–326.

Casalta, D., Guiard, Y., and Beaudouin-Lafon, M. 1999. Evaluating two-handed input techniques: rectangle editing and navigation. In *Proc. CHI Extended Abstracts*. 236–237.

Fingerworks.

Guiard, Y. 1987. Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *J. Motor Behavior 19(4)*, 486–517.

Hinckley, K., Pausch, R., Proffitt, D., Patten, J., and Kassell, N. 1997. Cooperative bimanual action. In *Proc. CHI*. 27–34.

Isokoski, P. and Käki, M. 2002. Comparison of two touchpad-based methods for numeric entry. In *Proc. CHI*. 25–32.

Kabbash, P., Buxton, W., and Sellen, A. 1994. Two–handed input in a compound task. In *Proc. CHI*. 417–423.

Karlson, A. K., Bederson, B. B., and SanGiovanni, J. 2005. AppLens and LaunchTile: Two Designs for One-Handed Thumb Use on Small Devices. In *Proc. CHI*. 201–210.

Költringer, T., Isokoski, P., and Grechenig, T. 2007. Twostick: Writing with a game controller. In *Proc. Graphics Interface*. 103–108.

Kurtenbach, G. 1993. The design and evaluation of marking menus. Ph.D. thesis, University of Toronto.

Kurtenbach, G. and Buxton, W. 1993. The limits of expert performance using hierarchic marking menus. In *Proc. CHI*. 258–264.

Kurtenbach, G. and Buxton, W. 1994. User learning and performance with marking menus. In *Proc. CHI*. 258–264.

Latulipe, C., Kaplan, C., and Clarke, C. 2005. Bimanual and unimanual image alignment: an evaluation of mouse-based techniques. In *Proc. UIST*. 123–131.

Latulipe, C., Mann, S., Kaplan, C., and Clarke, C. 2006. Symspline: Symmetric two-handed spline manipulation. In *Proc. CHI*. 349–358.

Lepinski, G. J., Grossman, T., and Fitzmaurice, G. 2010. The design and evaluation of multitouch marking menus. In *Proc. CHI*. 2233–2242.

McGuffin, M. J., Burtnyk, N., and Kurtenbach, G. 2002. Fast sliders: Integrating marking menus and the adjustment of continuous values. In *Proc. Graphics Interface*. 35–41.

MERL. Merl diamondtouch. http://merl.com/projects/DiamondTouch/.

Microsoft. Microsoft surface. http://www.microsoft.com/surface.

Moyle, M. and Cockburn, A. 2002. Analysing mouse and pen flick gestures. In *Proc. CHI*. 19–24.

Odell, D. L., Davis, R. C., Smith, A., and Wright, P. K. 2004. Toolglasses, marking menus, and hotkeys: a comparison of one and two-handed command selection techniques. In *Proc. Graphics Interface*. 17–24.

Owen, R., Kurtenbach, G., Fitzmaurice, G., Baudel, T., and Buxton, W. 2005. When it gets more difficult, use both hands: exploring bimanual curve manipulation. In *Proc. Graphics Interface*. 17–24.

PerceptivePixel. Perceptive Pixel. http://www.perceptivepixel.com/.

Perlin, K. 1998. Quikwriting: Continuous stylus-based text entry. In *Proc. UIST*. 215–217.

Potter, R. L., Weldon, L. J., and Shneiderman, B. 1988. Improving the accuracy of touch screens: an experimental evaluation of three strategies. In *Proc. CHI*. 27–32.

Weegie.

Wilson, A. D. and Agrawala, M. 2006. Text entry using a dual joystick game controller. In *Proc. CHI*. 475–478.

Yatani, K., Partridge, K., Bern, M., and Newman, M. W. 2008. Escape: a target selection technique using visually-cued gestures. In *Proc. CHI*. 285–294.

Zhao, S., Agrawala, M., and Hinckley, K. 2006. Zone and polygon menus: using relative position to increase the breadth of multi-stroke marking menus. In *Proc. CHI*. 1077–1086.

Zhao, S. and Balakrishnan, R. 2004. Simple vs. compound mark hierarchical marking menus. In *Proc. UIST*. 33–44.

Zhao, S., Dragicevic, P., Chignell, M., Balakrishnan, R., and Baudisch, P. 2007. Earpod: eyes-free menu selection using touch input and reactive audio feedback. In *Proc. CHI*. 1395–1404.

THIS DOCUMENT IS THE APPENDIX TO:

Two-Handed Marking Menus for Multitouch Devices

KENRICK KIN
University of California, Berkeley
Pixar Animation Studios
BJÖRN HARTMANN
University of California, Berkeley
and
MANEESH AGRAWALA
University of California, Berkeley

This document contains the full results of both the initial study as well as the longitudinal study.

A. RESULTS: IPOD TOUCH

Summaries of the average times and accuracies for all of the iPod Touch conditions are shown in Figures 19 and 20. Since each menu layout offers a different total number of accessible menu items we focus on comparing performance of the menu techniques within each menu layout rather than across layouts. For each menu layout and each dependent variable we computed a separate repeated measures ANOVA using menu technique as the only factor. For each menu layout we also compared performance differences between different combinations of stroke pairs. For the two-handed conditions we also consider differences in motion overlap and the effects of the starting hand on the ordered technique.

A.1 4-2 Menu Layout

Total Time: The average total times were 1149 ms for 1HL, 1065 ms for 1HR, 1003 ms for 2HS, and 1094 ms for 2HO. Menu technique had a significant effect on total time ($F_{3,45}$= 6.09, p=0.001). Pairwise t-tests show that average total times differed significantly for all pairs (p<0.007), except for the pairs 1HL-2HO (p=0.133), 1HR-2HS (p=0.142), and 1HR-2HO (p=0.439). In general total time was similar across the four conditions with increased reaction time making up for decreased movement time in the two-handed conditions.

Reaction Time: The average reaction times were 606 ms for 1HL, 572 ms for 1HR, 716 ms for 2HS, and 631 ms for 2HO. Menu technique had a significant effect on reaction time ($F_{3,45}$=19.19, p<0.001). Pairwise t-tests show that average reaction times differed significantly for all pairs (p<0.03), except for 1HL-2HO (p=0.277). Unlike movement time, reaction time was slowest for two-handed simultaneous.

Movement Time: The average movement times were 542 ms for 1HL, 493 ms for 1HR, 287 ms for 2HS, and 463 ms for 2HO. Menu technique had a significant effect on movement time ($F_{3,45}$=24.20, p<0.001). Pairwise t-tests show that average

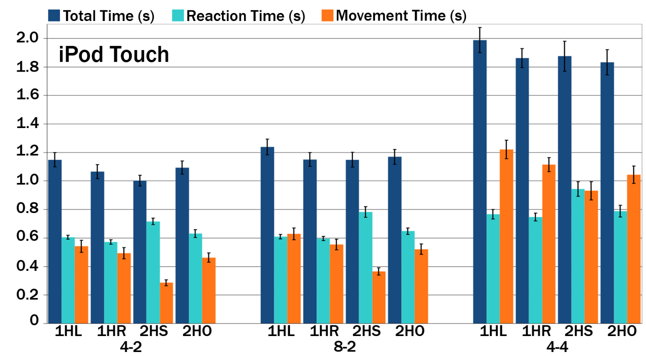

Fig. 19. Average total, reaction, and movement times (with std. error) for each menu technique and menu layout on the iPod Touch.

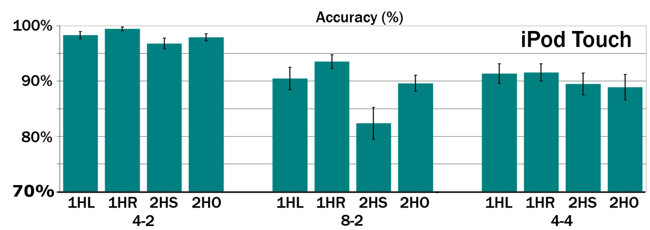

Fig. 20. Average accuracies (with std. error) for each menu technique and menu layout on the iPod Touch.

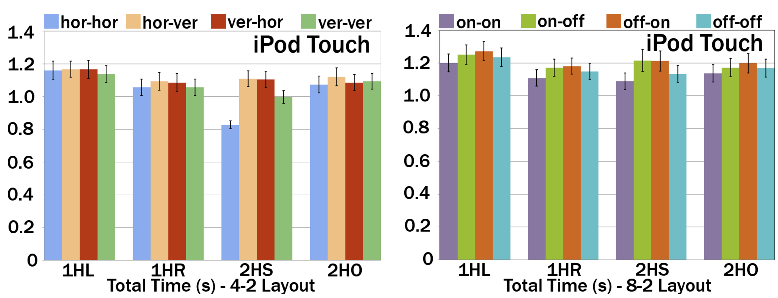

Fig. 21. Left: Average total times for horizontal or vertical stroke combinations for the 4-2 layout. Right: Average total times for on- or off-axis stroke combinations for the 8-2 layout. Both graphs are for the iPod Touch. Standard error bars are shown.

movement times differed significantly for all pairs ($p<0.03$), except for the pair 1HR-2HO ($p=0.285$). Movement for two-handed simultaneous was the fastest, movement for the right-handed multi-stroke and two-handed ordered were next fastest, and movement for the left-handed multi-stroke was the slowest.

Accuracy: The average accuracies were 98.3% for 1HL, 99.5% for 1HR, 96.8% for 2HS, and 97.9% for 2HO. There was no significant difference in accuracy ($F_{3,45}=2.29$, $p=0.091$) due to menu technique.

Horizontal and Vertical Strokes: For the 4-2 layout, we compared horizontal-horizontal, horizontal-vertical, vertical-
horizontal, and vertical-vertical selections for each menu technique. The average total times were usually longer for strokes along different axes as shown in Figure 21 (Left). Menu technique and the stroke combinations both had a significant effect on total time ($p<0.001$). There was also a significant interaction effect ($F_{9,135}=20.99$, $p<0.001$), which can be clearly seen in that 2HS has a very strong separation in performance in same-axis pairs compared to different-axis pairs, while the other techniques do not. There was no significant difference in accuracy.

Two-Handed Motion Overlap and Starting Hand: To assess the level of motion overlap in the two-handed conditions we computed the delay between the start of the touch with the first hand and the start of the touch with the second hand. A shorter delay indicates a greater likelihood of overlap between the hand motions. The average delay in the two-handed simultaneous condition was 35 ms, compared to 254 ms in the two-handed ordered condition ($p<0.001$). For 2HO we found no significant differences in time or accuracy between trials started with the left hand and those started with the right hand.

A.2 8-2 Menu Layout

Total Time: The average total times were 1238 ms for 1HL, 1151 ms for 1HR, 1148 ms for 2HS, and 1170 ms for 2HO. Menu technique had a significant effect on total time ($F_{3,45}= 5.27$, $p=0.003$). Pairwise t-tests show that average total times differed significantly for all pairs ($p<0.02$), except for the pairs 1HR-2HS ($p=0.918$), 1HR-2HO ($p=0.343$), and 2HS-2HO ($p=0.464$).

Reaction Time: The average reaction times were 610 ms for 1HL, 597 ms for 1HR, 783 ms for 2HS, and 648 ms for 2HO. Menu technique had a significant effect on reaction time ($F_{3,45}=29.09$, $p<0.001$). Pairwise t-tests show that average reaction times differed significantly for all pairs ($p<0.02$), except for the pair 1HL-1HR ($p=0.214$).

Movement Time: The average movement times were 629 ms for 1HL, 555 ms for 1HR, 366 ms for 2HS, and 521 ms for 2HO. Menu technique had a significant effect on movement time ($F_{3,45}=44.96$, $p<0.001$). Pairwise t-tests show that average movement times differed significantly for all pairs ($p<0.05$). The trend in movement times was similar to the 4-2 layout with two-handed simultaneous fastest and the left-handed condition slowest.

Accuracy: The average accuracies were 90.4% for 1HL, 93.5% for 1HR, 82.3% for 2HS, and 89.6% for 2HO. Menu technique had a significant effect on accuracy ($F_{3,45}=6.41$, $p=0.001$). Pairwise t-tests show that average accuracies differed significantly for all pairs ($p<0.05$), except for the pairs 1HL-1HR ($p=0.163$) and 1HL-2HO ($p=0.695$). Two-handed simultaneous had the lowest accuracy.

On- and Off-Axis Strokes: We compared on-on, on-off, off-on, and off-off axis selections for the 8-2 layout. The total times are shown in Figure 21 (Right). Menu technique ($p<0.01$) and the stroke combinations ($p<0.001$) both had a significant effect on total time. There was also a significant interaction effect ($F_{9,135}=2.38$, $p=0.02$), Combinations in which both strokes with either on axis or off-axis performed best. There was no significant difference in accuracy.

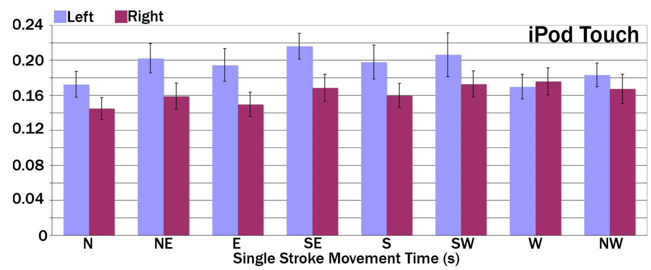

Fig. 22. First stroke average movement times (with std. error) for each direction on each hand using the iPod Touch for the 8-2 layout.

Single Stroke Directions: To better understand which individual stroke directions are easiest to make with the thumbs, we also examined examined the movement time of the first stroke in the 8-2 layout for both of the one-handed conditions as as shown in Figure 22. Pooling the data across all directions we found that the right hand (161 ms) was significantly faster than the left hand (191 ms) ($p=0.005$). For each hand we ran separate ANOVA's with stroke direction as the factor and found that stroke direction did significantly affect movement time for both the left hand ($F_{7,105}=3.74$, $p=0.001$) and the right hand ($F_{7,98}=3.46$, $p=0.002$). We removed one participant's data from the right hand analysis, as one of the stroke directions did not appear as the first stroke in any of that participant's trials. Examining the average movement times, we found that the left thumb was faster at selecting strokes in the upper left quadrant (N, NW, W directions) and the right thumb was faster at selecting strokes in the upper right quadrant (N, NE, E directions). In addition, on-axis stroke directions tended to be faster than their neighboring off-axis directions.

Two-Handed Motion Overlap and Starting Hand: The average delay between touches in the two-handed simultaneous condition was 52 ms, compared to 298 ms in the two-handed ordered condition ($p<0.001$), indicating more motion parallelism in the simultaneous condition. Again for the two-handed ordered technique we found no significant difference in speed or accuracy due to the starting hand of the stroke sequence.

A.3 4-4 Menu Layout

Total Time: The average total times were 1988 ms for 1HL, 1862 ms for 1HR, 1875 ms for 2HS, and 1832 ms for 2HO. Menu technique had a significant effect on total time ($F_{3,45}= 3.14$, $p=0.034$). Pairwise t-tests show that average total times differed significantly only for the pairs 1HL-1HR ($p=0.004$) and 1HL-2HO ($p=0.006$).

Reaction Time: The average reaction times were 767 ms for 1HL, 747 ms for 1HR, 944 ms for 2HS, and 788 ms for 2HO. Menu technique had a significant effect on reaction time ($F_{3,45}=17.01$, $p<0.001$). Pairwise t-tests show that average reaction times differed significantly only for two-handed simultaneous compared to each of the other menu techniques ($p<0.001$).

Movement Time: The average movement times were 1221 ms for 1HL, 1115 ms for 1HR, 931 ms for 2HS, and 1044 ms for 2HO. Menu technique had a significant effect on movement time ($F_{3,45}=18.74$, $p<0.001$). As in the 4-2 condition, pair-

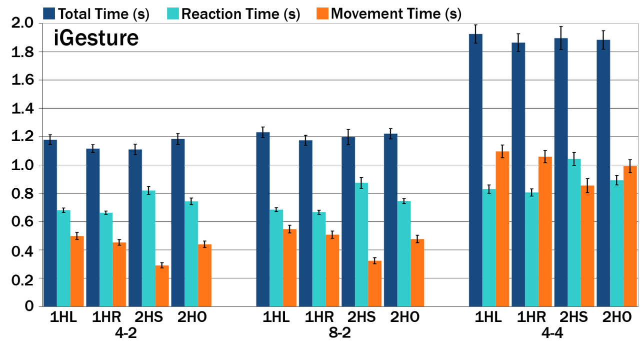

Fig. 23. Average total, reaction, and movement times (with std. error) for each menu technique and menu layout on the iGesture.

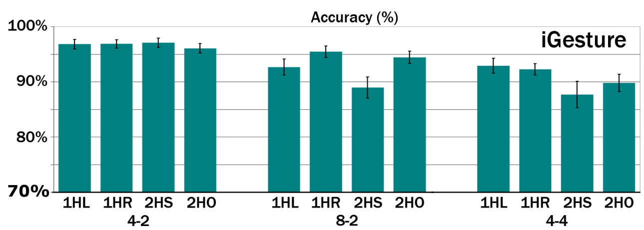

Fig. 24. Average accuracies (with std. error) for each menu technique and menu layout on the iGesture.

wise t-tests show that average movement times differed significantly for all pairs ($p<0.03$), except for the pair 1HR-2HO ($p=0.071$). This layout again followed the ordering of the 4-2 and 8-2 conditions with two-handed simultaneous fastest, left-handed slowest, and the other two layouts in between.

Accuracy: The average accuracies were 91.3% for 1HL, 91.6% for 1HR, 89.5% for 2HS, and 88.9% for 2HO. There was no significant difference in accuracy ($F_{3,45}=0.66$, $p=0.582$) due to menu technique.

Two-Handed Motion Overlap and Starting Hand: The average delay between touches in the two-handed simultaneous condition was 32 ms, compared to 268 ms in the two-handed ordered condition ($p<0.001$), indicating more motion parallelism in the simultaneous condition. Just as in the 4-2 and 8-2 cases, we found no significant difference due to starting hand for the two-handed ordered technique.

B. RESULTS: IGESTURE

Summaries of the average times and accuracies for all of the iGesture conditions are shown in Figures 23 and 24. Since each menu layout offers a different total number of accessible menu items we focus on comparing performance of the menu techniques within each menu layout rather than across layouts. For each menu layout and each dependent variable we computed a separate repeated measures ANOVA using menu technique as the only factor. For each menu layout we also compared performance differences between different combinations of stroke pairs.

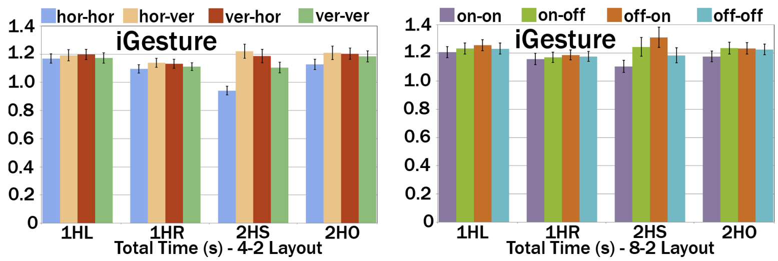

Fig. 25. Left: Average total times for horizontal or vertical stroke combinations for the 4-2 layout. Right: Average total times for on- or off-axis stroke combinations for the 8-2 layout. Both graphs are for the iGesture. Standard error bars are shown.

B.1 4-2 Menu Layout

Total Time: The average total times were 1179 ms for 1HL, 1116 ms for 1HR, 1110 ms for 2HS, and 1183 ms for 2HO. Menu technique had a significant effect on total time ($F_{3,45}$= 5.05, p=0.004). Pairwise t-tests show that average total times differed significantly for all pairs (p<0.03), except for the pairs 1HL-2HO (p=0.870) and 1HR-2HS (p=0.772). In general total time was similar across the four conditions with increased reaction time making up for decreased movement time in the two-handed conditions.

Reaction Time: The average reaction times were 680 ms for 1HL, 663 ms for 1HR, 819 ms for 2HS, and 743 ms for 2HO. Menu technique had a significant effect on reaction time ($F_{3,45}$=25.41, p<0.001). Pairwise t-tests show that average reaction times differed significantly for all pairs (p<0.01), except for the pair 1HL-1HR (p=0.242). Unlike movement time, reaction time was slowest for two-handed simultaneous.

Movement Time: The average movement times were 499 ms for 1HL, 452 ms for 1HR, 291 ms for 2HS, and 440 ms for 2HO. Menu technique had a significant effect on movement time ($F_{3,45}$=53.14, p<0.001). Pairwise t-tests show that average movement times differed significantly for all pairs (p<0.01), except for the pair 1HR-2HO (p=0.460). Movement for two-handed simultaneous was the fastest, movement for the right-handed multi-stroke and two-handed ordered were next fastest, and movement for the left-handed multi-stroke was the slowest.

Accuracy: The average accuracies were 96.8% for 1HL, 96.9% for 1HR, 97.1% for 2HS, and 96.1% for 2HO. There was no significant difference in accuracy ($F_{3,45}$=0.27, p<0.844) due to menu technique.

Horizontal and Vertical Strokes: For the 4-2 layout, we compared horizontal-horizontal, horizontal-vertical, vertical-horizontal, and vertical-vertical selections for each menu technique. The average total times are shown in Figure 25 (Left). Menu technique and stroke combination both had a significant effect on total time (p<0.01), and there was a significant interaction effect ($F_{9,135}$=20.05, p<0.001). There was no significant difference in accuracy for any of the menu techniques.

Two-Handed Motion Overlap and Starting Hand: To assess the level of motion overlap in the two-handed conditions we computed the delay between the start of the touch with the first hand and the start of the touch with the second

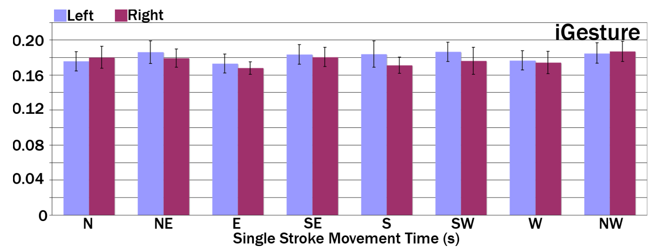

Fig. 26. First stroke average movement times (with std. error) for each direction on each hand using the iGesture for the 8-2 layout.

hand. A shorter delay indicates a greater likelihood of overlap between the hand motions. The average delay in the two-handed simultaneous condition was 47 ms, compared to 228 ms in the two-handed ordered condition ($p<0.001$). For the two-handed ordered condition we also compared the time and accuracy between trials started with the left hand and those started with the right hand. We found no significant differences.

B.2 8-2 Menu Layout

Total Time: The average total times were 1231 ms for 1HL, 1174 ms for 1HR, 1197 ms for 2HS, and 1221 ms for 2HO. Menu technique had no significant effect on total time ($F_{3,45}= 1.61$, $p=0.201$).

Reaction Time: The average reaction times were 684 ms for 1HL, 666 ms for 1HR, 874 ms for 2HS, and 744 ms for 2HO. Menu technique had a significant effect on reaction time ($F_{3,45}=35.81$, $p<0.001$). Pairwise t-tests show that average reaction times differed significantly for all pairs ($p<0.05$).

Movement Time: The average movement times were 547 ms for 1HL, 509 ms for 1HR, 324 ms for 2HS, and 477 ms for 2HO. Menu technique had a significant effect on movement time ($F_{3,45}=45.53$, $p<0.001$). As in the 4-2 layout, pairwise t-tests show that average movement times differed significantly for all pairs ($p<0.003$), except for the pair 1HR-2HO ($p=0.160$). The trend in movement times was also similar, with two-handed simultaneous fastest, the left handed condition slowest.

Accuracy: The average accuracies were 92.7% for 1HL, 95.5% for 1HR, 89.0% for 2HS, and 94.5% for 2HO. Menu technique had a significant effect on accuracy ($F_{3,45}=4.24$, $p=0.010$). Pairwise t-tests show that the only significant differences were between the pairs 1HR-2HS ($p=0.012$) and 2HS-2HO ($p=0.014$). Two-handed simultaneous had the lowest accuracy.

On- and Off-Axis Strokes: We compared on-on, on-off, off-on, and off-off axis selections for the 8-2 layout. The total times are shown in Figure 25 (Right). There was no significant effect on total time due to menu technique ($p=0.227$), but there was a significant effect due to on- or off-axis stroke combinations ($p<0.001$). There was also a significant interaction between menu technique and stroke combination ($F_{9,135}=6.864$, $p<0.001$). Accuracy was significantly different only for the two-handed simultaneous condition
($F_{3,45}=33.94$, $p=0.014$).

Single Stroke Directions: To better understand which individual stroke directions are easiest to make with the index or middle finger, we also examined examined the movement time of the first stroke in the 8-2 layout for both of the one-handed conditions as shown in Figure 26. Pooling the data across all directions we found that the movement time of the right hand (177 ms) was not significantly different than the movement time of the left hand (180 ms) ($p=0.693$). For each hand we ran separate ANOVA's with stroke direction as the factor and found that stroke direction also did not significantly affect movement time for the left hand ($F_{7,105}=0.58$, $p=0.773$) nor for the right hand ($F_{7,105}=0.83$ $p=0.564$)

Two-Handed Motion Overlap and Starting Hand: The average delay between touches in the two-handed simultaneous condition was 59 ms, compared to 263 ms in the two-handed ordered condition ($p<0.001$), indicating more motion parallelism in the simultaneous condition. Again for the two-handed ordered technique we found no significant difference in speed or accuracy due to the starting hand of the stroke sequence.

B.3 4-4 Menu Layout

Total Time: The average total times were 1926 ms for 1HL, 1864 ms for 1HR, 1897 ms for 2HS, and 1884 ms for 2HO. Menu technique had no significant effect on total time ($F_{3,45}= 0.78$, $p=0.513$).

Reaction Time: The average reaction times were 829 ms for 1HL, 805 ms for 1HR, 1043 ms for 2HS, and 893 ms for 2HO. Menu technique had a significant effect on reaction time ($F_{3,45}=37.27$, $p<0.001$). Pairwise t-tests show that average reaction times differed significantly for all pairs
($p<0.005$), except for 1HL-1HR ($p=0.193$).

Movement Time: The average movement times were 1097 ms for 1HL, 1059 ms for 1HR, 854 ms for 2HS, and 991 ms for 2HO. Menu technique had a significant effect on movement time ($F_{3,45}=21.73$, $p<0.001$). Pairwise t-tests show that average movement times differed significantly for all pairs ($p<0.01$), except for the pair 1HL-1HR ($p=0.131$). Movement for two-handed simultaneous was the fastest, and movement for the two-handed ordered was the second fastest. The one-handed conditions were the slowest.

Accuracy: The average accuracies were 92.9% for 1HL, 92.3% for 1HR, 87.7% for 2HS, and 89.8% for 2HO. There was no significant difference in accuracy ($F_{3,45}=2.36$, $p=0.084$) due to menu technique.

Two-Handed Motion Overlap and Starting Hand: The average delay between touches in the two-handed simultaneous condition was 38 ms, compared to 253 ms in the two-handed ordered condition ($p<0.001$), indicating more motion parallelism in the simultaneous condition. We found no significant difference due to starting hand for the two-handed ordered technique, except starting with the right hand had a faster reaction time (872 ms) than the left hand (914 ms) ($p=0.040$).

C. RESULTS: LONGITUDINAL STUDY

The longitudinal study was performed on the iPod Touch. Summaries of the average times and accuracies for all conditions are shown in Figure 27. We ran separate two-way ANOVAs with the factors menu technique and day on the times and accuracy of each layout.

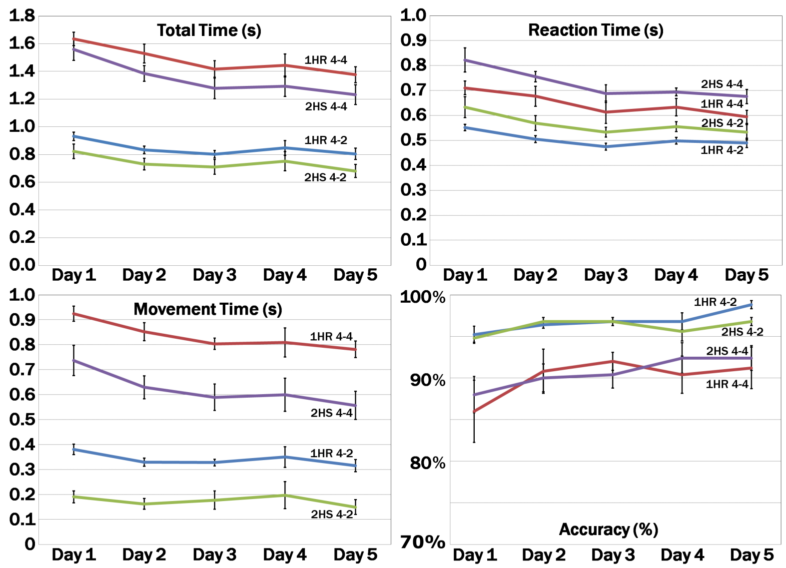

Fig. 27. Average time and accuracy (with std. error) for menu techniques 1HR and 2HS and menu layouts 4-2 and 4-4, across five days.

C.1 4-2 Menu Layout

Total Time: By day five, the average total time was 805 ms for 1HR and 682 ms for 2HS, reduced from 932 ms and 823 ms respectively on day one. Menu technique (p=0.005) and day (p=0.009) had significant effects on total time, but there was no interaction effect ($F_{4,16}$=0.308, p=0.869).

Reaction Time: By day five, the average reaction time was 590 ms for 1HR and 533 ms for 2HS, reduced from 552 ms and 633 ms respectively. The difference between 1HR and 2HS reaction times dropped from 81 ms to 57 ms (29.6%). Menu technique (p=0.012) and day (p<0.001) had significant effects on reaction time, but there was no interaction effect ($F_{4,16}$=0.907, p=0.483).

Movement Time: By day five, the average movement time was 315 ms for 1HR and 149 ms for 2HS, reduced from 380 ms and 190 ms respectively. The difference between 1HR and 2HS movement times dropped from 190 ms to 166 ms (12.6%). Menu technique (p=0.001) had a significant effect on movement time, whereas day did not (p=0.277). There was no interaction effect ($F_{4,16}$=1.263, p=0.325).

Accuracy: By day five, the average accuracy was 98.8% for 1HR and 96.8% for 2HS, increased from 95.2% and 94.8% respectively on day one. The day had a significant effect on accuracy (p=0.195) whereas the menu technique did not (p=0.195). There was no interaction effect ($F_{4,16}$=1.758, p=0.187).

Stroke Pairs: Figure 28 shows the total time in sorted order for each of the 16 stroke pairs in the 1HR condition (top) and the 2HS condition (bottom). For 2HS there is a large jump as the total time to perform a pair of strokes strokes that are bilaterally symmetric or in the same direction is faster than other stroke pairs by over 10%. There is no such jump for 1HR, but the pairs in which both strokes are drawn in the same direction are the four fastest.

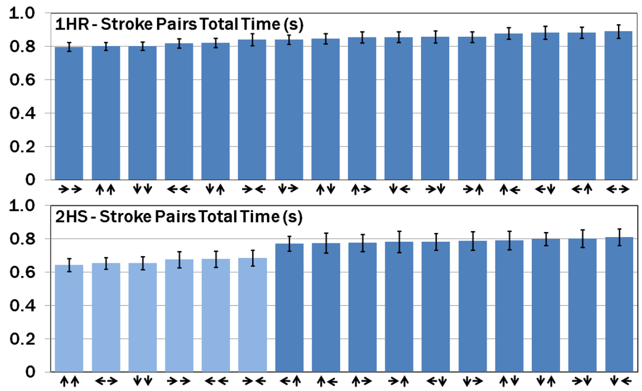

Fig. 28. Average total time (with std. error) per pair of strokes. For 2HS, the six fastest times belong to pairs of strokes that are bilaterally symmetric or share the same direction.

C.2 4-4 Menu Layout

Total Time: By day five, the average total time was 1376 ms for 1HR and 1234 ms for 2HS, reduced from 1635 ms and 1559 ms respectively on day one. Menu technique ($p=0.008$) and day ($p<0.001$) had significant effects on total time, but there was no interaction effect ($F_{4,16}=0.820$, $p=0.531$).

Reaction Time: By day five, the average reaction time was 594 ms for 1HR and 676 ms for 2HS, reduced from 711 ms and 822 ms respectively. The difference between 1HR and 2HS reaction times dropped from 111 ms to 82 ms (26.2%). Menu technique ($p=0.005$) and day ($p<0.001$) had significant effects on reaction time, but there was no interaction effect ($F_{4,16}=0.484$, $p=0.748$).

Movement Time: By day five, the average movement time was 782 ms for 1HR and 557 ms for 2HS, reduced from 924 ms and 737 ms respectively. The difference between 1HR and 2HS movement times dropped from 225 ms to 187 ms (16.9%). Menu technique ($p=0.001$) and day ($p<0.007$) had significant effects on movement time, but there was no interaction effect ($F_{4,16}=0.389$, $p=0.814$).

Accuracy: By day five, the average accuracy was 91.2% for 1HR and 92.4% for 2HS, increased from 86.0% and 88.0% respectively on day one. Neither menu technique ($p=0.774$) nor day ($p=0.084$) had a significant effect on accuracy. There was no interaction effect ($F_{4,16}=0.544$, $p=0.706$).

D. RESULTS: LONGITUDINAL STUDY - 8-2 MENU LAYOUT

A summary of the results are shown in Figure 29.

For block four, average total time was 864 ms for 1HR and 731 ms for 2HS, reduced from 908 ms and 864 ms respectively for block one.

For block four, average reaction time was 498 ms for 1HR and 531 ms for 2HS, reduced from 527 ms and 232 ms respectively for block one.

For block four, average movement time was 367 ms for 1HR and 200 ms for 2HS, reduced from 381 ms and 264 ms respectively for block one.

The average accuracies for block four, 83.2% ms for 1HR and 89.6% ms for 2HS, were similar to the respective accuracies for block one, 94.8% ms for 1HR and 89.1%

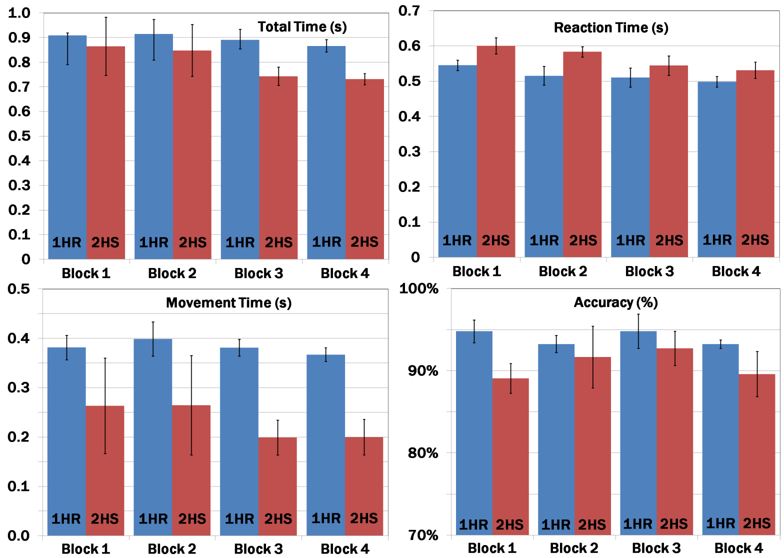

Fig. 29. Average time and accuracy (with std. error) for menu techniques 1HR and 2HS and menu layouts 4-2 and 4-4, across five days.

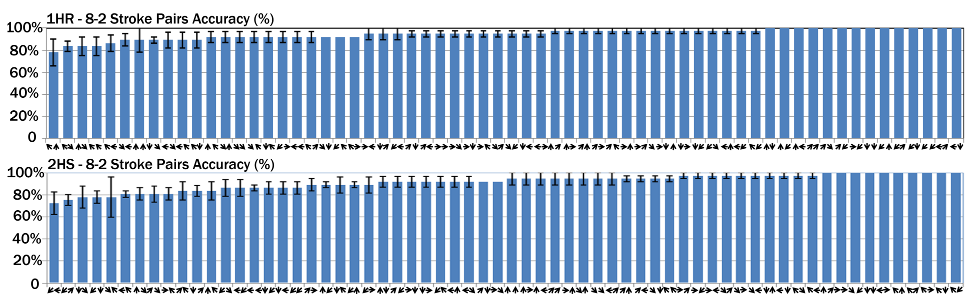

Fig. 30. Average accuracy for all stroke pairs in the 8-2 layout using the 1HR and 2HS technique. Note that standard error bars are zero when all three participants had the same accuracy.

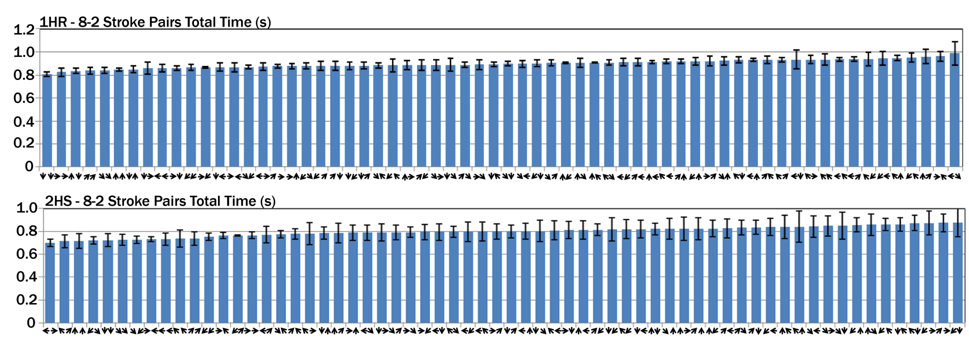

Fig. 31. Average total time (with std. error) for all stroke pairs in the 8-2 layout using the 1HR and 2HS technique.

for 2HS.

Stroke Pairs: Although 2HS is not quite as accurate as 1HR, examining the individual stroke pairs for 2HS (Figure 30), we find that when the left stroke is parallel to the SW-NE axis or the right stroke is parallel to the SE-NW axis accuracy drop to 86.6%, while the remaining 36 stroke pairs maintain an accuracy at 95.0%. Just as for the breadth-4 layout, we find that pairs of bilaterally symmetric or same-direction strokes (731 ms) are faster to draw than other pairs (815 ms). The average total time for each stroke pair is shown in Figure 31.